FINAL REPORT

on

NASA Grant NGR21-002-285

RESEARCH ON TECHNIQUES FOR LASER RANGING TO OPTICAL CORNER REFLECTORS ON THE MOON

1 July 1970 to 30 June 1971

RESEARCH ON LASER TECHNIQUES AND SINGLE PHOTO-ELECTRON DETECTION AND TIMING

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Prepared by

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June 1976

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COLLEGE PARK, MARYLAND

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Table of Contents

I. Introduction

The original grant was established to allow the Quantum Electronics Research Group in the Department of Physics and Astronomy of the University of Maryland, which had largely developed the equipment and techniques for the successful lunar laser ranging experiment, to continue research on new techniques for the improvement of the accuracy of the measurement. It was also intended to provide support for the Principal Investigator in his role as chairman of the newly constituted Lunar Laser Ranging Experiment Team to advise NASA on the conduct of the measurements and on the development of other ranging stations. The encouragement of groups in other countries to participate in the experiment and the coordination of their activities was also to be supported by the grant.

In June 1971, the policy was adopted by the Lunar Exploration Office of NASA not to support any research and development in relation to lunar laser ranging and, therefore, not to continue the grant. This policy was regarded as wrong by Dr. Harvey Hall and Mr. Marvin Redfield of the Office of Manned Space Flights of NASA and its Advanced Development Division. The grant was therefore continued under supplements 1, 2, and 3. In the summer of 1973, shortage of funds and a more restricted sense of mission in the Advanced Development section of the OMSF forced the termination of the grant on September 30, 1973.

Although the full realization of the goal of a field operable laser ranging system capable of one centimeter accuracy and lunar distance capability with modest sized optics was not achieved because of the termination, work has continued in this direction. Building on the foundation provided by this grant, support from the Office of Applications of NASA through

the Wallops Station, from the Office of Naval Research and from the Goddard Space Flight Center of NASA, has allowed substantial further programs and accomplishment toward the goal. Since the research program has been a continuous one from the standpoint of the Quantum Electronics Research Group, the accomplishments during the period since the conclusion of the subject grant will be summarized along with those achieved during the grant period.

II. Accomplishments During the Grant Period

A. Research on Single Photo-Electron Detection and Timing

Experimental studies using a pulsed LED, Cerenkov source, and 100 ps laser were made of various photomultipliers and discriminator combinations in close cooperation with the manufacturers. The RCA Tube C31024 was found to exhibit a spread of only 0.45 nanoseconds (full width at half maximum). The investigations were published in six papers, Numbers 1, 2, 3, 9, 10, and 14 in section IV below, and have been extensively referred to by other workers. The review article by Professor Poultney (No. 9) has been of particular value. Some work on a green/red timing difference for certain photomultipliers will be published in the future.

B. Laser Research and Development

The basis for this work has been a new type of Neodymium-YAG frequency doubled laser originally constructed under contract from the Advanced Research Projects Agency through the Office of Naval Research by the Sylvania Company. The purpose of the support was to advance the art of stable, short pulse, high repetition rate, laser systems. Thus Dr. John McCallum of ARPA and Dr. Fred Quelle of ONR agreed to give the completed system to the University of Maryland for research under this NASA grant. Originally expected in June 1971, delivery was finally completed by Sylvania in July 1972. However, it did not perform as specified and was extensively redesigned and rebuilt at the University of Maryland.

The overall concept of an acousto-optic mode-locked oscillator, followed by electro-optic pulse selection into a multi-pass amplifier, with electro-optic pulse extraction and frequency doubling was retained. Major changes

were made to the oscillator head (rebuilding and replacing incandescent air-cooled pumping lamps with water-cooled krypton arc lamps); to the acousto-optic mode locker (adding crystal controlled 75 MHz oscillator and increasing the drive power); to the Pockels Cell drive circuits (replacing gas tube switches with avalanche transistor chains and synchronizing stably to the 75 MHz oscillator); to the beam deviators (changing from damage-prone calcite prisms to thin film polarizers); to the multi-pass amplifier (adding a diffusing sleeve around the Nd-YAG rod, using many passes with small gain per pass to prevent spontaneous oscillation, and adjustment of the pin-hole size to yield diffraction limited operation); and to the water-cooling and power supply systems (substitution of more reliable components). In addition, changes of mirror curvatures and reflectivities and laser rod end curvatures and lengths were made. The laser is discussed briefly in publication 15 of section IV of this report. A detailed paper is in preparation.

These changes, and many smaller ones, were largely accomplished by the summer of 1974, resulting in a laser operating reliability with the following characteristics:

Pulse Length:	120 picoseconds, full width at half maximum
Pulse Shape:	Gaussian
Pulse Energy (at 5321 Å):	0.4 millijoules
Repetition Rate:	30 pulses per second
Amplitude Stability:	± 2 precent
Beam Divergence:	Diffraction limited, ∿ 0.4 milli-radian

During the grant period, and subsequently, attention has been given to amplifier design and construction to produce 0.5 joules per pulse while re-

taining the other characteristics. A Ph.D. thesis which includes a thorough analysis of the physics of such amplifiers and computer simulation for design purposes has been nearly completed by John Degnan. Implementation will be under the plans discussed in section III-B of this report.

Our successful operation of this type of laser has influenced the design of the second lunar ranging station in Hawaii and the considerations at the Goddard Space Flight Center for future artificial satellite tracking stations. Also the very stable and reproducible short pulses we have demonstrated has caused the laser fusion activity at the Lawrence Livermore Laboratory to begin construction of this type of system for its injection laser because of the difficulties with large amplitude fluctuations and missed pulses they have experienced with their dye mode-locked with spark gap extraction systems.

C. Development of International Cooperation in Lunar Laser Ranging

During the period of the grant, through the initiative of the Principal Investigator and colleagues in other countries, chiefly Professor Jean Kovalevsky of France, there was established at the 1970 meeting of COSPAR in Leningrad a special working panel for lunar laser ranging under Working Group 1 (Satellite Tracking) of COSPAR. Sponsorship of the panel was broadened at the 1970 meeting of the International Astronomical Union in Brighton to include the IAU. In 1971 at the meeting of the International Union of Geodesy and Geophysics in Moscow, the IUGG became a sponsor by making the panel a study group of the International Association of Geodesy.

The Principal Investigator served as chairman of this COSPAR/IAU/IUGG panel until June 1975. Annual reports were prepared for COSPAR of the activities in other countries. Much effort was invested to encourage international participation in Lunar Ranging, including trips and lectures. There is now lunar ranging activity, including station development, in France, the

Soviet Union, Japan, Australia, and the United Kingdom. There is hope for future activity in India, Brazil, South Africa, and Czechoslovakia. There is need for a world wide network of stations to realize the full potential of the lunar ranging technique for the study of fluctuations in the earth's rotation rate (UTO), the position of the pole, and the global plate tectonic motions. In 1977 a coordinated international effort under the auspices of the COSPAR/IAU/IUGG panel for the study of the earth's rotation will be conducted. It is called Earth Rotation from Lunar Distances (EROLD). It is expected that more accuracy and the ability to resolve shorter term fluctuations than conventional methods will be demonstrated.

III. Later Research Made Possible by This Grant

A. Atomic Clock General Relativity and Laser Pulse Remote Time Comparison Experiments Using An Aircraft.

With support from the U.S. Naval Observatory, the Director of Navy Laboratories and the Office of Naval Research, from December 1, 1973 to the present, very successful experiments have been carried out to measure with atomic clocks the effect of gravitational potential on elapsed time as predicted by Einstein in his General Theory of Relativity. An important part of the experiment was the use of the short pulse laser described in section II-B of this report, along with timing techniques discussed in section II-A, to compare time at a distance using reflected light pulses as described by Einstein in his original 1905 paper on relativity. Some of the significant aspects of the experiments are:

> First accurate measurement ($\sim$1%) of the effect of curved space-time on macroscopic clocks.
>
> Completely convincing demonstration of the reality of these remarkable effects.
>
> First demonstration of high resolution comparison ($\sim$ 0.3 nanoseconds) comparison of time at a distance using short laser pulses.
>
> Stability of a few points in 10^{14} is possible with existing commercial atomic clocks with careful control of the environment, even aboard an aircraft.
>
> First practical applications of Einstein's curved space-time theory of gravitation are in the requirements of terrestrial time keeping with stable clocks. The dependence of elapsed time differences on gravitational potential differences and on velocity differences must be taken into account.

The successful demonstration of the laser pulse time comparison is of relevance to the new Department of Defense Global Positioning System in which atomic clocks will be orbited in 12 hour period satellites. It is expected

that the Navy will support development of space qualified photo-detector and event-timer (see publication 12 in Section IV) equipment.

B. Research Program on Laser Ranging with the 48-inch Telescope at the Goddard Space Flight Center.

The laser pulse remote time comparison system described in section III-A above also constituted a laser ranging system. It was the first field operational system capable of one centimeter resolution. This accomplishment was supported in part by a grant from NASA/GSFC effective on April 1, 1975. The main purpose of the grant is to allow us to use our laser and timing equipment on the new 48-inch telescope to make experiments in ranging to satellites. The use of single photo-electron detection and timing has been very successful in lunar ranging - larger signals are not possible. However, the technique has not yet been studied with the much nearer earth satellites.

It is expected that amplifiers will be added to our laser to allow ranging to an artificial earth satellite without corner reflectors (the so-called "shiny ball" satellite), to the LAGEOS satellite, and to the Lunar Laser Ranging Retro-Reflectors (LR^3's). The research with the 48-inch telescope has been delayed by the atomic clock relativity experiments, but the equipment is now being installed and ranging experiments are expected during the summer of 1976.

IV. Publications Supported in Whole or in Part by the Grant

1. PHOTOCATHODE QUANTUM EFFICIENCY ENHANCEMENT OF THE RCA 31000E PHOTOMULTIPLIER AT 6328 Å, by S. K. Poultney and R. Lakes, Applied Optics 9, 2192 (1970).

2. SUBNANOSECOND SINGLE PHOTOELECTRON TIMING RESOLUTION OF THE RCA 31000E PHOTOMULTIPLIER USING ORTEC CONSTANT FRACTION DISCRIMINATORS AND MONSANTO LIGHT-EMITTING DIODES, by S. K. Poultney and R. Lakes, Review of Scientific Instruments 41, 1889 (1970).

3. DIRECT MEASUREMENT OF THE QUANTUM COUNTING EFFICIENCY OF A RCA C31000E PHOTOMULTIPLIER AT 6328 Å, by S. K. Poultney and R. Lakes, Applied Optics 10, 797 (1971).

4. A TRIGGERABLE SUB-NANOSECOND LIGHT SOURCE, by C. A. Steggerda, University of Maryland Department of Physics and Astronomy Technical Report No. 71-086, 1971.

5. THE FAR FIELD DIFFRACTION PATTERN FOR CORNER REFLECTORS WITH COMPLEX REFLECTION COEFFICIENTS, by R. F. Chang, D. G. Currie, M. F. Pittman, and C. O. Alley, Journal of the Optical Society of America 61, p. 431, April 1971.

6. OPTICAL PROPERTIES OF THE APOLLO LASER RETRO-REFLECTOR ARRAYS, by R. F. Chang, D. G. Currie, C. O. Alley and J. E. Faller, Space Research XII, Proceedings of the Fourteenth Plenary Session of COSPAR, Seattle, 1971. Akademie-Verlag, Berlin, 1971.

7. THE LUNAR LASER RANGING EXPERIMENT, by P. L. Bender, R. H. Dicke, D. T. Wilkinson, C. O. Alley, D. G. Currie, J. E. Faller, J. D. Mulholland, E. C. Silverberg, H. H. Plotkin, W. M. Kaula, and G. J. F. MacDonald, in the Proceedings of the Conference on Experimental Tests of Gravitation Theories, held at the California Institute of Technology, November 1970. Published in Jet Propulsion Laboratory Technical Memorandum 33-499, p. 178 (November 1971).

8. FUTURE POSSIBILITIES FOR THE LUNAR LASER RANGING EXPERIMENT, by D. G. Currie, C. O. Alley, and S. K. Poultney, Space Research XII, Proceedings of the Fourteenth Plenary Session of COSPAR, Seattle, 1971. Akademie-Verlag, Berlin, 1972.

9. SINGLE PHOTON DETECTION AND TIMING: A REVIEW OF EXPERIMENTS AND TECHNIQUES, by S. K. Poultney, Advances in Electronics and Electron Physics (L. Marton, Ed.), Vol. 31, pp. 39 to 114, Academic Press, New York, 1972.

10. SINGLE PHOTON DETECTION AND TIMING IN THE LUNAR LASER RANGING EXPERIMENT, by S. K. Poultney, IEEE Transactions on Nuclear Science NS-19 No. 3, p. 12 (1972).

11. STORY OF THE DEVELOPMENT OF THE APOLLO 11 LASER RANGING RETRO-REFLECTOR EXPERIMENT, ONE RESEARCHER'S PERSONAL ACCOUNT, by C. O. Alley in Adventures in Experimental Physics, Edited by B. Maglic, 1972, pp. 132-156, World Science Communications, Princeton, 1972.

12. SECOND GENERATION TIMING SYSTEM FOR THE APOLLO LUNAR LASER RANGING EXPERIMENT, by D. G. Currie, C. A. Steggerda, J. D. Rayner, and A. Buennagel, Proceedings of the Fourth Annual NASA and Department of Defense Precise Time and Time Interval (PTTI) Planning Meeting, Goddard Space Flight Center, November 14-16, 1972.

13. THE LUNAR LASER RANGING EXPERIMENT, by P. L. Bender, D. G. Currie, R. H. Dicke, ... and C. O. Alley, Science 182, pp. 229-238 (19 October 1973).

14. SINGLE PHOTON DETECTION AND SUB NANOSECOND TIMING RESOLUTION WITH THE RCA C31034 PHOTOMULTIPLIER, by S. K. Poultney, R. Reisse, and R. Creecy, Review of Scientific Instruments 44, 999 (1973).

15. THE UNIVERSITY OF MARYLAND LASER RANGING SYSTEM, by C. O. Alley, in the Proceedings of the Second Workshop on Laser Tracking Instrumentation held at the Faculty of Nuclear Science and Physical Engineering, Technical University of Prague, Edited by G. Weiffenbach and K. Hamal, August 1975.